

CONTENTS

| | |
|--|-----------|
| FORWARD | iii |
| EXECUTIVE SUMMARY | v. |
| FIGURES | xi |
| TABLES | xii |
| ABBREVIATIONS, ACRONYMS, AND SYMBOLS | xiii |
| SECTION 1.0 SUMMARY OF THE DESIGN METHODOLOGY | 1 |
| 1.1 OBJECTIVES AND DESIGN STRUCTURE | 1 |
| 1.2 PRELIMINARY ASSESSMENT TO DETERMINE SUITABILITY OF A SITE FOR PERMEABLE BARRIER APPLICATIONS | 3 |
| 1.3 SITE CHARACTERIZATION TO SUPPORT PERMEABLE BARRIER DESIGN | 5 |
| 1.4 REACTIVE MEDIA SELECTION | 6 |
| 1.5 TREATABILITY TESTING TO GENERATE CONTAMINANT- AND SITE- SPECIFIC DESIGN DATA | 7 |
| 1.6 MODELING TO SUPPORT BARRIER DESIGN AND DEVELOP MONITORING PLAN | 8 |
| 1.7 EMPLACEMENT OF THE BARRIER | 9 |
| 1.8 MONITORING THE PERFORMANCE OF THE BARRIER | 9 |
| 1.9 PERMEABLE BARRIER ECONOMICS | 9 |
| SECTION 2.0 TECHNOLOGY BACKGROUND AND STATUS | 11 |
| 2.1 PROBLEM DESCRIPTION | 11 |
| 2.2 TECHNOLOGY DESCRIPTION | 12 |
| 2.3 MECHANISM OF ENHANCED ABIOTIC DEGRADATION WITH METALS | 13 |
| 2.4 POTENTIAL BIOLOGICALLY MEDIATED REACTIONS IN THE REACTIVE CELL | 18 |
| 2.5 CURRENT STATUS OF PERMEABLE BARRIER FIELD APPLICATIONS | 18 |
| 2.6 EFFORTS OF GOVERNMENT AGENCIES TO PROVIDE REGULATORY GUIDANCE FOR THE USE OF PERMEABLE BARRIERS | 18 |
| SECTION 3.0 SITE CHARACTERIZATION DATA | 23 |
| 3.1 GROUNDWATER FLOW SYSTEM CHARACTERISTICS | 23 |
| 3.1.1 Site Background Information | 23 |
| 3.1.2 Hydrostratigraphic Framework | 23 |
| 3.1.3 Hydrologic Parameter Estimation | 24 |
| 3.2 ORGANIC COMPOSITION OF THE GROUNDWATER | 24 |
| 3.2.1 Organic Contaminant Spatial Distribution | 24 |
| 3.2.2 Groundwater Sampling and Analysis | 24 |
| 3.2.2 Groundwater Sampling for Volatile Organic Compounds (VOCs) | 25 |
| 3.2.3 Analytical Methods for VOCs | 25 |
| 3.3 INORGANIC COMPOSITION OF THE GROUNDWATER | 26 |
| 3.3.1 Sampling and Analysis of Field Parameters | 26 |
| 3.3.2 Sampling and Analysis for Inorganic Chemical Parameters | 27 |
| SECTION 4.0 REACTIVE MEDIA SELECTION | 28 |
| 4.1 TYPES OF REACTIVE MEDIA AVAILABLE | 28 |
| 4.1.1 Granular Zero-Valent Metal | 28 |

CONTENTS

(Continued)

| | |
|--|-----------|
| 4.1.1.1 Granular Iron | 28 |
| 4.1.1.2 Other Zero-Valent Metals | 29 |
| 4.1.2 Granular Iron with an Amendment | 30 |
| 4.1.3 Bimetallic Media | 30 |
| 4.1.4 Other Innovative Reactive Media | 31 |
| 4.1.4.1 Cercona™ Iron Foam | 31 |
| 4.1.4.2 Colloidal Iron | 31 |
| 4.1.4.3 Ferrous Iron-Containing Compounds | 31 |
| 4.1.4.4 Reduction of Aquifer Materials by Dithionite | 32 |
| 4.2 SCREENING AND SELECTION OF REACTIVE MEDIA | 32 |
| SECTION 5.0 TREATABILITY TESTING | 34 |
| 5.1 BATCH TESTING | 35 |
| 5.2 COLUMN TESTING | 35 |
| 5.2.1 Design and Implementation of Column Tests | 35 |
| 5.2.2 Interpreting Column Data | 38 |
| 5.2.3 Safety Factors | 41 |
| 5.2.4 Determining Flowthrough Thickness of the Reactive Cell | 42 |
| 5.3 ACCELERATED AND LONG-TERM COLUMN TESTING | 43 |
| 5.4 ESTIMATING THE PERMEABILITY OF THE SELECTED REACTIVE MEDIUM | 43 |
| SECTION 6.0 MODELING TO SUPPORT THE PERMEABLE BARRIER DESIGN | 45 |
| 6.1 HYDROGEOLOGIC MODELING APPROACH FOR DESIGN AND MONITORING OF PERMEABLE BARRIERS | 46 |
| 6.1.1 Modeling Approach for Relatively Homogeneous Aquifers | 46 |
| 6.1.2 Modeling Approach for Heterogeneous Aquifers | 48 |
| 6.1.3 Modeling Different Permeable Barrier Configurations and Dimensions | 48 |
| 6.2 GEOCHEMICAL EVALUATION FOR PERMEABLE BARRIER DESIGN AND PERFORMANCE | 54 |
| SECTION 7.0 EMPLACEMENT TECHNIQUES FOR PERMEABLE BARRIER INSTALLATION | 56 |
| 7.1 COMMERCIALLY AVAILABLE TECHNIQUES FOR REACTIVE CELL EMPLACEMENT | 56 |
| 7.1.1 Conventional Trench Excavation | 57 |
| 7.1.1.1 Backhoes | 59 |
| 7.1.1.2 Clamshells | 59 |
| 7.1.2 Caisson-Based Emplacement | 61 |
| 7.1.3 Mandrel-Based Emplacement | 62 |
| 7.1.4 Continuous Trenching | 62 |
| 7.2 COMMERCIALLY AVAILABLE TECHNIQUES FOR FUNNEL WALL EMPLACEMENT | 64 |
| 7.2.1 Steel Sheet Piles | 65 |
| 7.2.2 Slurry Walls | 67 |
| 7.2.2.1 Soil-Bentonite Slurry Wall | 67 |
| 7.2.2.2 Cement-Bentonite Slurry Wall | 68 |
| 7.2.2.3 Plastic Concrete Slurry Wall | 68 |

CONTENTS

(Continued)

| | |
|--|-----|
| 7.2.2.4 Composite Barrier Slurry Wall | 68 |
| 7.3 INNOVATIVE EMPLACEMENT TECHNIQUES | 70 |
| 7.3.1 Jetting | 70 |
| 7.3.2 Emplaced Hydraulic Fracturing | 72 |
| 7.3.3 Deep Soil Mixing | 72 |
| 7.4 CONSTRUCTION QUALITY CONTROL (CQC) | 74 |
| 7.5 HEALTH AND SAFETY ISSUES | 74 |
| 7.5.1 Waste Minimization | 74 |
| SECTION 8.0 MONITORING THE PERFORMANCE OF A PERMEABLE BARRIER | 76 |
| 8.1 ADEQUACY OF PLUME CAPTURE AND TREATMENT | 76 |
| 8.1.1 Monitoring for Potential Breakthrough or Bypass of Contaminants | 76 |
| 8.1.2 Sampling and Analysis for Contaminants and Byproducts | 81 |
| 8.1.3 Monitoring Downgradient Water Quality | 82 |
| 8.2 DETERMINING IF THE BARRIER MEETS DESIGN SPECIFICATIONS | 82 |
| 8.2.1 Estimating Residence Time Distribution in the Reactive Cell | 82 |
| 8.2.2 Estimating the Hydraulic Capture Zone Size | 83 |
| 8.3 ESTIMATING THE LONGEVITY OF THE BARRIER | 85 |
| SECTION 9.0 PERMEABLE BARRIER ECONOMICS | 87 |
| 9.1 CAPITAL COST CONSIDERATIONS | 87 |
| 9.2 OPERATING AND MAINTENANCE (O&M) COST CONSIDERATIONS | 88 |
| 9.3 COST-BENEFIT EVALUATION | 89 |
| 9.4 COMPUTERIZED COST MODELS | 89 |
| SECTION 10.0 REFERENCES | 93 |
| APPENDIX A: ADDITIONAL SITE CHARACTERIZATION AND MONITORING ISSUES | A-1 |
| APPENDIX B: SUPPORTING INFORMATION FOR HYDROGEOLOGIC MODELING | B-1 |
| APPENDIX C: SUPPORTING INFORMATION FOR GEOCHEMICAL MODELING | C-1 |
| APPENDIX D: CONSTRUCTION QUALITY CONTROL | D-1 |
| APPENDIX E: SELECTED SITE SUMMARIES OF PREVIOUS PERMEABLE BARRIER APPLICATIONS FOR CHLORINATED SOLVENT PLUMES | E-1 |

FIGURES

| | |
|---|----|
| Figure 1-1. Steps in the Design of a Permeable Barrier System | 2 |
| Figure 1-2. Decision Chart for Permeable Barrier Design Activities | 4 |
| Figure 2-1. Schematic Illustrations of Some Permeable Barrier Configurations | 12 |
| Figure 2-2. (a) Funnel-and-Gate System with Straight Funnel. (b) Other Possible Funnel-and-Gate System Configurations | 14 |
| Figure 2-3. Schematic of Proposed Degradation Process for TCE | 16 |
| Figure 5-1. Typical Column Setup | 36 |
| Figure 5-2. Photograph of Column Setup | 36 |
| Figure 5-3. Column Concentration Profile of TCE and One of Its Byproducts, cis-DCE | 39 |

CONTENTS

(Continued)

| | |
|--|----|
| Figure 5-4. Psuedo First-Order Degradation Rate of TCE | 39 |
| Figure 5-5. Example of a Column Profile of VOC Concentrations | 40 |
| Figure 5-6. Correlation of TCE Degradation Rates with Temperature..... | 42 |
| Figure 6-1. Simulated Particle Pathlines Showing Capture Zone..... | 47 |
| Figure 6-2. MFA Funnel-and-Gate Backward Particle Tracking Showing the Effect of Heterogeneity on Capture Zones. | 49 |
| Figure 6-3. Simulated Capture Zone for a Continuous Barrier Scenario Showing Flowpaths for 180 Days..... | 50 |
| Figure 6-4. Capture Zone for a Permeable Barrier with Two Caissons and Funnel Walls. Flowpaths for 5,000 Days Shown | 52 |
| Figure 7-1. Various Permeable Barrier Configurations | 58 |
| Figure 7-2. Emplacement of Reactive Iron Media (Suspended Bag) and Pea Gravel (Front-End Loader) into Divided Sections of a Permeable Cell. | 59 |
| Figure 7-3. Conventional Backhoe Excavation of a Slurry Cutoff Wall | 60 |
| Figure 7-4. Trench Excavation Using a Clamshell and Backhoe | 60 |
| Figure 7-5. Emplaced Caisson Being Augered Out, Somersworth Sanitary Landfill, New Hampshire | 61 |
| Figure 7-6. Continuous Trencher in Operation..... | 63 |
| Figure 7-7. Types of Slurry Wall Emplacement. (a) Keyed-In Emplacement and (b) Hanging Wall Emplacement..... | 64 |
| Figure 7-8. Sheet Piles Emplaced Using a Vibrating Hammer..... | 65 |
| Figure 7-9. Waterloo Barrier Sheet Piles | 66 |
| Figure 7-10. Cross-Section of a Soil-Bentonite Slurry Trench, Showing Excavation and Backfilling Operations | 67 |
| Figure 7-11. Composite Barrier Design. (a) Monitoring Wall Cross Section and (b) Section of HDPE Liner Envelope..... | 69 |
| Figure 7-12. Diagram of (a) Plan View of a Grouted Impermeable Barrier, (b) Geometric Layout of Grouted Injection Holes, and (c) Vertical Thin Diaphragm Walls..... | 71 |
| Figure 7-13. Deep Soil Mixing | 73 |
| Figure 8-1. Various Monitoring Well Configurations for Evaluating Performance of the Barrier | 77 |
| Figure 8-2. Concentrations of Chlorinated Compounds Along Center Line in the Flowpath of Existing Permeable Barrier | 79 |
| Figure 8-3. Installation of Monitoring Wells in the Reactive Cell and Pea Gravel..... | 80 |
| Figure 8-4. Possible Monitoring Well Configurations to Evaluate Hydraulic Capture Zone | 84 |
| Figure 9-1. RACER Version 3.2 Process Flowchart..... | 91 |

TABLES

| | |
|--|----|
| Table 1-1. Compounds Tested and Half-Lives Normalized to 1 m² Iron Surface per mL Solution | 5 |
| Table 2-1. Properties of Common Chlorinated Organic Compounds | 11 |
| Table 2-2. Current Status of Permeable Barrier Applications for Chlorinated Solvent Sites | 19 |
| Table 3-1. Requirements for Field Parameters and Inorganic Analytes | 26 |
| Table 7-1. Summary Table of Various Techniques for Barrier Emplacement | 57 |

ABBREVIATIONS, ACRONYMS, AND SYMBOLS

| | |
|----------------------|---|
| 2-D | two-dimensional |
| 3-D | three-dimensional |
| AFB | Air Force Base |
| AL/EQ | Armstrong Laboratory Environics Directorate |
| BET | Brunauer-Emmett-Teller Adsorption Isotherm Equation |
| bgs | below ground surface |
| BTEX | benzene, toluene, ethylbenzene, xylenes |
| CMC | carboxymethyl cellulose |
| CMS | Corrective Measures Study |
| CP | cone penetrometer |
| CPT | cone penetrometer test |
| CQC | construction quality control |
| DCE | dichloroethene |
| DNAPL | dense, nonaqueous-phase liquid |
| DO | dissolved oxygen |
| DOC | dissolved organic carbon |
| EDS | energy dispersive x-ray spectroscopy |
| Eh | redox potential |
| EPA | Environmental Protection Agency |
| EQL | estimated quantitation limit |
| ETI | EnviroMetal Technologies, Inc. |
| FGDM | Funnel-and-Gate Design Model |
| FID | flame ionization detector |
| GC | gas chromatography |
| GC-FID | gas chromatograph-flame ionization detector |
| GE | General Electric |
| GX | gum xanthan |
| HDPE | high-density polyethylene |
| HFB | Horizontal Flow Barrier |
| HSU | hydrostratigraphic units |
| IAP | ion activity product |
| IC | ion chromatography |
| ICP | inductively coupled plasma |
| ITRC | Interstate Technology and Regulatory Cooperation |
| K | hydraulic conductivity |
| K _{aquifer} | aquifer hydraulic conductivity |
| K _{een} | reactive cell hydraulic conductivity |

| | |
|----------|---|
| MCL | maximum contaminant level |
| MFA | Moffett Federal Airfield |
| MS | matrix spike |
| MSDS | Material Safety Data Sheet |
| NERL | National Exposure Research Laboratory |
| NFESC | Naval Facilities Engineering Service Center |
| NPV | net present value |
| NRC | National Research Council |
| O&M | operating and maintenance |
| ORC | oxygen-releasing compound |
| OSHA | Occupational Safety and Health Administration |
| PBWG | Permeable Barriers Working Group |
| PCB | polychlorinated biphenyl |
| PCE | perchloroethylene |
| PPE | personal protective equipment |
| PRP | potentially responsible party |
| QA | quality assurance |
| QAPP | Quality Assurance Project Plan |
| QC | quality control |
| RCRA | Resource Conservation and Recovery Act |
| RFI | RCRA Facility Investigation |
| RFI/CMS | RFI/Corrective Measures Study |
| RI/FS | Remedial Investigation/Feasibility Study |
| ROD | Record of Decision |
| RTDF | Remediation Technologies Development Forum |
| SEM | scanning electron microscopy |
| SI | saturation index |
| SITE | Superfund Innovative Technology Evaluation |
| SPH | smooth particle hydrodynamics |
| T | temperature |
| TCA | trichloroethane |
| TCE | trichloroethylene |
| TDS | total dissolved solids |
| TOC | total organic carbon |
| TSS | total suspended solids |
| USCG | United States Coast Guard |
| U.S. DOE | U.S. Department of Energy |
| U.S. EPA | U.S. Environmental Protection Agency |
| USGS | United States Geological Survey |
| UST | underground storage tank |

| | |
|-----|------------------------------|
| VC | vinyl chloride |
| VOC | volatile organic compound |
| VP | vinyl polymer |
| WDS | wave dispersive spectroscopy |
| XRD | x-ray diffraction |